Task 4: Extended Summary
Radionuclides Released from X-10 to the Clinch River via White Oak Creek

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Purpose

The purpose of Task 4 of the Oak Ridge Dose Reconstruction is (1) to estimate the historical releases from the X-10 facility to the Clinch River, (2) to evaluate the potential pathways by which members of the public could have been exposed to radioactive effluents in the Clinch River from 1944 to 1991, and (3) to calculate radiation doses and risks to reference individuals who were potentially exposed to radioactivity released to the Clinch River from the X-10 facility. Direct measurement of the amount of radionuclides taken up by the organs of specific individuals since 1944 is no longer feasible because most of these radionuclides have short residence times in the human body. Therefore, a dose reconstruction has been necessary to determine the magnitude and extent of past exposure and to interpret the health consequences of these exposures. This dose reconstruction relies upon independent evaluation of the amount of radionuclides released, reported environmental measurements, and mathematical models to estimate the magnitude and extent of past exposures, doses, and health risks.

Background

In the early days of the Manhattan Project, the Clinton Laboratory, later referred to as the X-10 facility and now called the Oak Ridge National Laboratory, was designed to operate for one year as a pilot plant for the Hanford, Washington, operations. All radioactive wastes generated from this facility were to be stored in large underground "gunite" tanks. The original plans changed, and in 1944 the first radioactive effluents from the X-10 site entered White Oak Creek and flowed into White Oak Lake. White Oak Lake served as the final settling basin for contaminants released to White Oak Creek. Radionuclides remaining in the water column were released from the X-10 site with the flow of water from White Oak Dam, which is located 1 km (0.6 mile) upstream from the Clinch River.

Sources of Radioactive Waste

During the early years of X-10 operations, the graphite reactor and the "hot pilot plant" (a chemical separation plant) were the major source of radioactive wastes. Wastes from the "hot pilot plant" were placed in open waste pits; high levels of ^{106}Ru began seeping from the pits into White Oak Lake in 1959. Strontium-90 and ^{137}Cs had also been placed in the pits, but these isotopes were retained by nearby soils; however, amounts of ^{106}Ru as high as 7.4×10^{13} Bq (2000 curies) per year were released from White Oak Dam from 1959 to 1963. From 1944 to 1991, approximately 5.9×10^{15} Bq (160,000 curies) of radioactivity were released over White Oak Dam to the Clinch River; of this amount, 91% was tritium, and the rest was mixed fission and activation products.

Evidence suggests that a secondary source of radionuclides released to the Clinch River was the scouring of contaminated sediment from White Oak Creek Embayment. After White Oak Lake was drained in 1955, heavy rainfall scoured the bottom sediment of White Oak Lake, resulting in the deposition of particle reactive radionuclides (primarily ^{137}Cs) in White Oak Creek Embayment. The peaking discharges from Melton Hill Dam, which was completed in 1963, resulted in the backflow of water up White Oak Creek Embayment and the scouring of radionuclide-containing sediments into the Clinch River. A coffer cell dam was constructed at the mouth of White Oak Creek in 1990 to prevent the backflow of water up White Oak Creek Embayment, and scouring of embayment sediment ceased at that time.

Screening Analysis

To focus time and resources on the radionuclides that were most likely to have been important in terms of dose or risk to off-site individuals, a conservative screening evaluation was conducted. Twenty-four radionuclides released into the Clinch River from the X-10 site from 1944 to 1991 were considered as potential contaminants of concern. The conservative screening analysis identified those radionuclides and pathways for which the human health risk was clearly below a minimum level of concern. Nine exposure pathways and sixteen radionuclides, including tritium, were identified as low priority for further consideration because conservative screening estimates were at least a factor of ten below the screening criterion of one chance in ten thousand (1×10^{-4}) of excess incidence of disease, as established by the Oak Ridge Health Agreement Steering Panel (ORHASP). Of the eight remaining radionuclides, ^{137}Cs, ^{60}Co, ^{106}Ru, and ^{90}Sr were expected to be the most important contributors to radiological dose and subsequent excess health risk.

Radionuclides Released from White Oak Dam

The dose reconstruction relies on estimates and reported measurements of radionuclides released from White Oak Dam from 1944-1991. A detailed investigation was performed for (1) the methods used for measurements of radioactive releases from White Oak Dam, (2) the methods used for estimation of flow rates at White Oak Dam, and (3) the uncertainties associated with these measurements. Estimates of the quantities of radionuclides historically released from White Oak Dam were based on laboratory documents, available log books, and interviews with personnel who were responsible for, or involved in, the collection of samples and monitoring of radioactive releases at White Oak Dam. Direct measurements of the radionuclides released from White Oak Dam were available, except for the years 1944 to 1949. For these years, estimates were based on the fraction that each radionuclide contributed to a measurement or estimate of gross beta activity. Detailed source terms (annual release amounts) were developed for the following radionuclides: ^{60}Co, ^{90}Sr, ^{95}Nb, ^{95}Zr, ^{106}Ru, ^{131}I, ^{137}Cs, and ^{144}Ce. The uncertainty of the source terms varied over time because of various changes in sampling and analytical methods and waste disposal or treatment events.

Estimated Radionuclide Concentrations in Water and Sediments

Measured concentrations of radionuclides in water are available for many years for several locations downstream from the confluence of White Oak Creek and the Clinch River (CRM 20.8). These measurements were not entirely consistent as to location or method of measurement and did not include all the radionuclides of concern. Therefore, a modeling effort was conducted to estimate the annual average concentrations of radionuclides in water at specific locations downstream of White Oak Creek. A modified version of the HEC-6 aquatic transport model (HEC-6-R) was used to estimate historical water concentrations. The annual average releases of specific radionuclides from White Oak Dam were used in the modeling analysis. The uncertainty of the modeled water concentrations was much higher than the uncertainty about water concentrations obtained from measured data; therefore, measured data for specific locations and time periods were used in preference to model predictions when the data were sufficient to estimate an annual average concentration in water. In particular, the model did not always account sufficiently for localized scouring of sediment after Melton Hill Dam began operation in 1963.

Estimated shoreline concentrations of radionuclides in sediment were obtained by using the HEC-6-R model to track the sediment inventory in various reaches of the Clinch River. Monitoring data collected in the 1990s were used to calibrate the shoreline sediment estimates. Because of the limited data, all shoreline sediment concentrations used in the risk assessment were based on model estimates.

Estimation of Exposure to Reference Individuals

For all locations, the exposure pathways of interest include fish ingestion and ingestion of milk and meat; other exposure pathways of interest varied with location. For the Jones Island area (CRM 21.0 to 17.0), the exposure pathways of interest were fish ingestion, external exposure from shoreline sediment, and ingestion of meat and milk. The exposure pathways for the K-25/Grassy Creek area (CRM 17.0 to CRM 5.0) included fish ingestion, drinking water, external exposure to shoreline sediment, and ingestion of milk and meat. For the Kingston Steam Plant area (CRM 5.0 to CRM 2.0), the important pathways were drinking water, fish ingestion, external exposure to shoreline sediment, and ingestion of milk and meat. Exposure pathways for residents of the City of Kingston (CRM 2.0 to CRM 0.0) included fish ingestion, external exposure to shoreline sediment, drinking water, and ingestion of milk and meat from livestock having direct access to the river as a source of drinking water.

Reference individuals in this study were identified with respect to the pathways involved, the specific characteristics of the individual pathways, and the size and type of the population affected. For the fish pathway, the reference individuals were defined as Category I (people who consumed fish on a regular basis, i.e., 1 to 2.5 meals per week or 7.1 – 33 kg y^{-1} for males and 5.7 – 27 kg y^{-1} for females), Category II (0.25 – 1.3 meals per week or 2.2 – 16 kg y^{-1} for males and 1.8 – 14 kg y^{-1} for females), and Category III (0.04 – 0.33 meals per week or 0.39 – 4.3 kg y^{-1} for males and 0.32 – 3.6 kg y^{-1} for females). (Meal size was defined as 0.10 – 0.30 kg per meal for males and 0.08 – 0.25 kg per meal for females. The ranges shown are the 95% subjective confidence intervals and do not include the extreme values on either end.) For all categories, it was assumed that 20 to 100% of the fish was contaminated and that 80 to 90% of the radioactivity in the fish was retained after processing.

Two reference individuals, an adult and a child, were used for the water ingestion pathway. Children were not considered for the K-25/Grassy Creek area or the Kingston Steam Plant area, because these are industrial facilities and it is not likely that children would have obtained drinking water from these locations. However, both children and adults were exposed via the City of Kingston water supply. Multiple reference individuals were considered for the milk ingestion pathway, including children who could have consumed different amounts of home-produced milk depending on whether they were at home or in school. Adults were considered as the reference individuals for both the meat ingestion pathway and the external exposure pathway. External exposure calculations were based on shoreline usage of 75 – 430 h y^{-1} at CRM 20.5, 85 – 440 h y^{-1} at CRM 14, or 130 – 490 h y^{-1} CRM 3.5 or CRM 0 (95% subjective confidence internals).

Estimation of Organ-Specific Radiation Doses

The International Commission on Radiological Protection (ICRP) has developed a methodology to calculate internal radiation doses to people ingesting contaminated food or drinking contaminated water. To account for the uncertainties introduced by variability among individuals, a range of values was developed for the factors that specify the dose per unit intake for a given radionuclide. To obtain the ranges of possible values for ^{137}Cs, ^{60}Co, and ^{106}Ru, the published ICRP ingestion dose factors were modified by application of multiplicative uncertainty factors, the values of which were dependent on the radionuclide and organ. In addition, new dose conversion factors and associated uncertainties were calculated for ^{90}Sr and ^{131}I, based on the ICRP methodology. Dose conversion factors were derived for all internal organs of importance. A sensitivity analysis was performed to determine which of the biokinetic parameters contribute the most to the uncertainty in the dose conversion factors. Each dose conversion factor was specified as a range of values rather than a point estimate.

Fish Ingestion

The estimated organ doses to individuals consuming fish exceeded the dose estimates for all other pathways. The highest doses were for Category I consumers of fish (1-2.5 meals per week) at CRM 20.5, just below the confluence of White Oak Creek and the Clinch River. Central values of the cumulative doses for 1944 to 1991 for specific organs ranged from 0.31 (skin) to 0.81 cSv (bone) for males and from 0.23 (skin) to 0.60 cSv (bone) for females (1 cSv equals 1 rem); the 95% subjective confidence intervals ranged from about 0.02 to 8 cSv. Organ doses were generally lower for females than for males, due to the lower ingestion rate assumed for females. For Category I consumers of fish near the city of Kingston (CRM 0), the organ doses are about a factor of 8-9 lower than those estimated for CRM 20.5. Estimated organ doses for Category II and III consumers of fish are lower than those for Category I in proportion to the lower intake rates assumed for these categories of individuals.

Other exposure pathways

Organ-specific doses from external exposure were about a factor of 1.1-3.5 lower than the doses to a Category I consumer of fish at CRM 14, with the largest doses to skin, bone, and thyroid. Adults who spent time along the shoreline but who seldom consumed fish probably received the same or higher organ doses from external exposure as from fish ingestion.

For most organs, doses from drinking water at CRM 14 and CRM 3.5 from 1946 – 1960 were lower than the doses from external exposure at the same location. However, for the large intestine, bone, and red bone marrow, the doses from drinking water were higher than those from external exposure or consumption of fish (by Category II or III consumers) due to the presence of ^{90}Sr and ^{106}Ru.

Estimated doses from ingestion of meat and milk were lower than those for ingestion of drinking water by 1 to 3 orders of magnitude. The highest doses were to the large intestine, bone, red bone marrow, and (for the ingestion of milk) the thyroid.

Estimates of thyroid dose to a child from the drinking water and milk ingestion pathways

The 95% subjective confidence interval for the estimated doses to a child 0 to 14 years of age drinking milk at CRM 14 or CRM 3.5 were 0.00058 to 0.054 cSv (0.0062 central value) and 0.00055 to 0.042 cSv (0.0044 central value), respectively. The 95% subjective confidence interval for the estimated drinking water dose for a child living in Kingston (CRM 0.0) was 0.000039 to 0.0021 cSv (0.00031 central value), and for the combined pathways (drinking water and milk), 0.00014 to 0.0047 cSv (0.00091 central value). The exposure period for a child drinking water or water and milk was different from that for drinking milk alone because the Kingston City municipal water supply did not become a potential source of contamination until 1955.

Estimates of Excess Lifetime Risk of Cancer Incidence

The organ-specific dose estimates were used as the basis for organ-specific and total estimates of excess lifetime risk of cancer incidence. The dose-response functions were based on cancer incidence data from the Japanese A-bomb survivors, the background incidence of cancer for East Tennessee, and the use of relative versus absolute risk models to transfer epidemiological findings in the A-bomb survivors to populations exposed to radionuclides released to the Clinch River. The uncertainty due to differences between exposures at high and low dose rates was considered explicitly in the calculation of risk for each organ. Extension of the calculations from dose to risk accounts for differing radiosensitivity among organs and permits identification of the most important target organs. In addition, estimation of the risks facilitates direct interpretation of the exposures in terms of their potential impact on people's health.

Fish Ingestion

For Category I consumers of fish (1 – 2.5 meals per week) near Jones Island (CRM 20.5), the 95% subjective confidence interval of the total excess lifetime risk of cancer incidence for all radionuclides and organs was 3.6 X 10^{-5} to 3.5 x 10^{-3} (central value, 2.8 x 10^{-3}) for males and 2.9 x 10^{-5} to 2.8 x 10^{-3} (central value, 2.3 x 10^{-4}) for females. The difference in risk between males and females primarily reflects the difference in ingestion rates. For both males and females, the largest contribution to the total risk (about 90%) is from ^{137}Cs.

For any given location, risks of excess lifetime cancer incidence for Category I consumers of fish are greater than those for Category II and III consumers by factors of about 2 and 8, respectively, in proportion to the lower intake rates assumed for these reference individuals. The upper bound on the total risk from fish consumption for a Category I or II consumers (1-2.5 or 0.25-1.3 meals per week, respectively) reaches or exceeds a reference lever of 1 x 10^{-4} at all locations; central values exceed a reference level of 1 x 10^{-4} only for Category I and II consumers at CRM 20.5. For Category III consumers (0.04-0.33 meals per week), the upper 95% subjective confidence limit on the total risk estimate is below a reference level of a x 10^{-4} for all locations except CRM 20.5.

For ingestion of fish from the Jones Island Area (CRM 20.5), the upper bounds on the risk for both males and females exceeded a reference level of 1 x 10^{-4} for bladder, stomach, lower large intestine, lungs, and red bone marrow (leukemia), as did the upper bounds on the risk estimates for breast in females and for liver in males. Although the breast received among the lowest doses of any organ, the breast has the highest risk of all the organs examined (upper bound, 9.3 x 10^{-4}). The highest risk for males and second highest risk for females is for the red bone marrow (upper bounds of 3.4 x 10^{-4} and 4.0 x 10^{-4}, respectively). The difference between the highest and lowest organ-specific risks at any one location is about a factor of 70-80 for females and 40 for males, although the differences in doses were only a factor of 2-4. This situation illustrates the great difference in organ sensitivities to radiation-induced cancer and underlines the importance of calculating risks as well as doses in a dose reconstruction study, because the organ with the highest dose may not be the organ at highest risk.

For individuals using or residing on Watts Bar Reservoir, the exposures, doses, and risks are substantially lower than they are for individuals using any segment of the Clinch River. Our best estimate is that exposures from the past consumption of contaminated fish in Watts Bar Reservoir are 4 to 25 times less than for persons catching fish from the Clinch River near the K-25/Grassy Creek area (CRM 14), assuming similar ingestion rates.

Other exposure pathways

Depending on the location, the external dose from shoreline sediments (based on exposure of approximately 100-500 h y^{-1}, depending on location) contributes as much as 90% of the total risk from all pathways for a Category III consumer of fish (0.04-0.33 meals per week); fish ingestion contributes about 10%, and drinking water from 2 to 30% of the total risk of cancer incidence. For Category II consumers of fish (0.25-1.3 meals per week), fish ingestion contributes 30-40% of the total risk, depending on location, and for Category I (1-2.5 meals per week), about 50-60%, except for CRM 20.5, where the external exposure is low and exposure via drinking water did not occur. For the external exposure pathway alone, the upper bounds at all locations except CRM 20.5 barely reach a reference level of 1×10^{-4} (highest value, 1.2×10^{-4} at CRM 0), indicating a low likelihood that this level was actually exceeded; for drinking water alone, the upper bound at all locations is below a reference level of 1×10^{-4} (highest value 4.6×10^{-5} at CRM 14). For the combined pathways at CRM 20.5, the upper bounds on the total excess lifetime risk were 3.6×10^{-3}, 1.7×10^{-3}, and 4.1×10^{-4} for male consumers of fish in Categories I, II, and III, respectively. For the other locations, the highest upper bound values were 5.9×10^{-4}, 3.4×10^{-4}, and 1.9×10^{-4} for male consumers of fish in Categories I, II, and III, respectively, at all CRM 14.

Estimates of excess lifetime risk of thyroid cancer for a child from the drinking water and milk ingestion pathways

The highest excess lifetime risk of thyroid cancer occurred for a female child ingesting milk obtained from an area near CRM 14 between 1946 and 1960 (95% confidence interval, 1.1×10^{-7} to 2.5×10^{-5}; central value, 1.8×10^{-6}). The 95% subjective confidence interval on the risk for a female child exposed via the combined drinking water and milk ingestion pathways (milk from CRM 3.5 and water from CRM 0, between 1955 and 1969) was 2.4×10^{-9} to 1.8×10^{-6} (central value, 2.4 c 10^{-7}).

Risk Estimates for Shorter Exposure Periods

In most cases, individuals were not exposed to the various pathways over the entire period from 1944 to 1991. In addition, both the operations at the X-10 site and the releases of radionuclides to the Clinch River changed over time. To account for more realistic exposure times, risks were summarized by decade.

The first two decades (1944-1953 and 1954-1963) produced the highest risks for each pathway and from all pathways combined. In the first decade, the ingestion of fish dominated the total risk; however, external exposure to shoreline sediments became increasingly important in later years. Because the ingestion of fish and external exposure to shoreline sediments contribute most of the excess lifetime risk of cancer incidence, ^{137}Cs is the dominant radionuclide in all decades. In addition to risk estimates by decade, estimates of total risk per year at CRM 14 were also made in terms of risk per pound of fish consumed, per hour exposed to shoreline sediment, and per liter of water consumed.

Contribution to Uncertainty in the Risk Estimates

This study explicitly included uncertainty in external dosimetry, internal dosimetry, and dose-response relationships (risk factos), as well as uncertainty in the various parameters affecting the exposure estimates. For all locations and ingestion rates examined, the dominant sources of uncertainty in the risk from fish ingestion are the concentration of ^{137}Cs in fish and the amount of fish consumed. The relative importance of a specific parameter depends on the location of exposure and the ingestion rates; in most cases, the bioconcentration factor is the single most important parameter affecting the overall uncertainty. For external exposure, the most important contributors to uncertainty are the concentrations of ^{137}Cs and ^{60}Co in shoreline sediments, followed by the total exposures and the risk factors. For internal exposure via drinking water, the most important sources of uncertainty are the amount of contaminant consumed, followed by the risk factors and the concentrations of ^{106}Ru and ^{90}Sr in the water. Uncertainty in dosimetry contributes less than 5% (internal) or 10% (external) of the total uncertainty, which the risk factor (except for internal exposure to ^{137}Cs) contributes 20-30%. Uncertainties in exposure parameter (radionuclide concentrations and amounts of exposure) are dominant for all pathways.

Results of Special Scenarios

Some individuals are thought to have consumed fish bones as well as flesh, in the form of fish patties. Therefore, an evaluation was made of the doses and risks resulting from substitution of part (8-20%) of a Category I consumer's fish intake with fish patties rather than flesh alone. The doses and risks to bone and red bone marrow are increased approximately 15-25% due to the increased ingestion of ^{90}Sr from the fish bones. However, because ^{90}Sr is a small contributor to total dose and risk from fish ingestion, the overall risk is not increased significantly by consumption of fish patties.

Four additional scenarios for internal exposure to radionuclides were evaluated, specifically the consumption of contaminated wildlife (fish, turtles, deer, or waterfowl) from the Oak Ridge Reservation. The risks per meal (4–16 ounces) were estimated for the highest reported contaminant levels and for more likely levels. For the most contaminated animals, the risk per meal ranged as high as 3 x 10^{-4}. Risks per meal for more likely values did not exceed 2 x 10^{-6}. For deer and waterfowl, risks were also calculated on a per animal basis. The number of people exposed to contaminated animals from the Oak Ridge Reservation has not been determined precisely, but it is thought to be a very small fraction of the total population exposed to contaminated fish, water, or sediment.

Advancements in Dose Reconstruction Studies

This report highlights several advancements in the field of dose reconstruction:

(1) Environmental measurements of radionuclide concentrations in water and mathematical models for predicting radionuclide concentrations in water and sediment were combined in a single analysis.

(2) Both modeled and measured concentrations of radionuclides in water and sediment were adjusted for the existence of known sources of bias and uncertainty.

(3) Site-specific data in conjunction with an evaluation of the scientific literature were used to estimate site-specific bioconcentration factors for Clinch River fish.

(4) Detailed information about the demography of the region from 1944 to 1991 permitted the specification of categories of individuals who could have been exposed and thereby the characterization of the variability among individuals in the exposed population.

(5) Every effort was made to ensure a realistic analysis of exposure, dose, and risk, and all sources of uncertainty were included in the final risk estimates.

(6) This dose reconstruction is one of the first in which uncertainty in both external and internal dosimetry is expressed explicitly and the dose-response relationship of cancer incidence with its uncertainty is expressed for each organ and for total cancers.

(7) Extending the calculations to risk accounted for differing radiosensitivity among organs and permitted accurate identification of the organs of most importance.

Conclusions

The radiological doses and excess lifetime cancer risks estimated in this report are incremental increases above those resulting from exposure to background sources of radiation in the East Tennessee region. Nevertheless, for the exposure pathways considered in this task, the doses and risks are not large enough for a commensurate increase in health effects in the population to be detectable, even by the most thorough of epidemiological investigations. In most cases, the estimated organ doses are clearly below the limits of epidemiological detection (1 to 30 cSv) for radiation-induced health outcomes that have been observed following irradiation of large cohorts of individuals exposed either in utero, as children, or as adults.

Even in the case of Category I consumers of fish, the upper confidence limits on the highest estimated organ-specific doses are below 10 cSv, and the central values are below 1 cSv. The lower confidence limits on these doses are well below levels that have been considered as limits of epidemiological detection in studies of cohorts of other exposed populations. The large uncertainty, combined with the small number of individuals comprising Category I consumers, diminishes the statistical power available to detect a dose response through epidemiological investigation. Therefore, it is unlikely that any observed trends in the incidence of disease in populations that utilized the Clinch River and Lower Watts Bar Reservoir after 1944 could be conclusively attributed to exposure to radionuclides released from the X-10 site, even though this present dose reconstruction study has identified increased individual risks as high as 1×10^{-3} resulting from these exposures.